

Lepton Number Violation in Decays of Supersymmetric Particles

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We discuss lepton flavour violating signals at the LHC in the framework of supersymmetric theories. We consider R-parity conserving as well as R-parity violating scenarios. In the case of R-parity conservation we show that in decays of supersymmetric particles large regions in parameter exist where lepton flavour violating decay modes have large branching ratios despite the stringent constraints from the non-observation of rare lepton decays. We discuss briefly some consequences for discovery potential and the measurements of edge-variables at LHC within the SPS1a scenario. In the case of R-parity violating scenarios we focus on bilinear R-parity violation. We discuss correlations between the decays of the lightest neutralino and neutrino mixing angles as well as the possibilities to measure these correlations at LHC.

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1 Introduction

The observed neutrino oscillations [1, 2, 3] are a clear indication for non-vanishing neutrino masses and violation of individual lepton numbers. Supersymmetry (SUSY) offers many possibilities to describe the observed neutrino data. The most popular one is certainly the usual seesaw mechanism [4], which introduces heavy right-handed neutrinos carrying a $\Delta L = 2$ lepton number violating Majorana mass. In the Minimal Supersymmetric Standard Model (MSSM) a large ν_μ - ν_τ mixing can lead to a large $\tilde{\nu}_\mu$ - $\tilde{\nu}_\tau$ mixing via renormalisation group equations [5]. An additional source of lepton flavour violation (LFV) arise in models where the MSSM with R-parity conservation is embedded in a GUT theory [6]. This is a consequence of having leptons and quarks in the same GUT multiplet. The quark flavour mixing due to the CKM matrix leaves its traces also in the leptonic sector [6, 7].

Therefore, one expects flavour violating effects for charged leptons. Furthermore, in analogy to quarks, lepton flavour violation may also be related to CP violation. Lepton flavour violation (LFV) in the charged lepton sector is, however, severely constrained by the stringent experimental bounds on the branching ratios $BR(\mu \rightarrow e\gamma) < 1.2 \cdot 10^{-11}$, $BR(\tau \rightarrow e\gamma) < 2.7 \cdot 10^{-6}$, $BR(\tau \rightarrow \mu\gamma) < 1.1 \cdot 10^{-6}$ and rare processes such as $\mu - e$ conversion [8]. Nevertheless, clear LFV signals are expected in slepton and sneutrino production and in the decays of neutralinos, charginos, sleptons and sneutrinos at the LHC and at future lepton colliders [9, 10, 11] despite these stringent constraints. We will discuss such scenarios in the first half of this report.

Supersymmetry offers an interesting option to accommodate for the observed

neutrino data which is intrinsically supersymmetric: the breaking of R-parity. Adding bilinear terms to the MSSM superpotential is the simplest way to realize this idea in practice. It has been shown that in this way neutrino data can be successfully explained (see e.g. [12] and references therein). Moreover it has been demonstrated that various decay properties of the lightest supersymmetric particle (LSP) are correlated with neutrino properties, in particular with neutrino mixing angles [13, 14]. We will discuss such correlations taking the lightest neutralino as LSP as well as the possibilities to measure these correlations at the LHC.

2 The R-parity conserving MSSM

We will first discuss the case of conserved R-parity where total lepton number is conserved but individual lepton is violated. In the absence of right-handed neutrinos one can work without loss of generality in a basis where the lepton Yukawa couplings are real and diagonal. In this basis the complete information on LFV is encoded in the mass matrices of the charged sleptons and of the sneutrinos:

$$M_l^2 = \begin{pmatrix} M_{LL}^2 & M_{LR}^{2\dagger} \\ M_{LR}^2 & M_{RR}^2 \end{pmatrix}, \quad M_{\bar{\nu},ij}^2 = M_{L,ij}^2 + \frac{1}{8}(g^2 + g'^2)(v_d^2 - v_u^2)\delta_{ij} \quad (1)$$

where the entries in M_l^2 are 3×3 matrices that are given by

$$M_{LL,ij}^2 = M_{L,ij}^2 + \frac{1}{2}(v_d Y_i^E)^2 \delta_{ij} + \frac{1}{8}(g'^2 - g^2)(v_d^2 - v_u^2)\delta_{ij}, \quad (2)$$

$$M_{LR,ij}^2 = \frac{1}{\sqrt{2}}(v_d A_{ij}^* - \mu v_u Y_i^E \delta_{ij}), \quad (3)$$

$$M_{RR,ij}^2 = M_{E,ij}^2 + \frac{1}{2}(v_d Y_i^E)^2 \delta_{ij} - \frac{1}{4}g'^2(v_d^2 - v_u^2)\delta_{ij}. \quad (4)$$

M_L^2 and M_E^2 are the soft SUSY breaking mass matrices for left and right sleptons, respectively, and the A_{ij} are the trilinear soft SUSY breaking couplings of the sleptons and Higgs boson, μ and the Y_l^E are the usual μ parameter and the lepton Yukawa couplings such that $m_l = v_d Y_l^E / \sqrt{2}$. v_u and v_d are the vacuum expectation values of the neutral Higgs fields (with $\tan \beta = v_u / v_d$).

In the following we are interested in the effect of the off-diagonal entries in the matrices M_L^2 , M_E^2 and A_{ij} . For this reason we fix the diagonal entries of these matrices as well as the other supersymmetric parameters by using the original high scale definition of the Snowmass point SPS#1a [15]: $M_0 = 100$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -100$ GeV, $\tan \beta = 10$ and $\mu > 0$. At the electroweak scale typical parameters are given as $M_{L,11}^2 = 202.3^2$ GeV², $M_{L,33}^2 = 201.5^2$ GeV², $M_{E,11}^2 = 138.7^2$ GeV², $M_{E,33}^2 = 136.3^2$ GeV², $A_{11} = -7.567 \cdot 10^{-3}$ GeV, $A_{22} = -1.565$ GeV, $A_{33} = -26.326$ GeV. To these parameters we add off-diagonal elements such that the bounds from rare lepton decays are fulfilled. We find values for $|M_{E,ij}^2|$ up to $8 \cdot 10^3$ GeV², $|M_{L,ij}^2|$ up to $6 \cdot 10^3$ GeV² and $|A_{ij} v_d|$ up to 650 GeV² compatible with the constraints. In most cases, one of the mass squared parameters is at least one order of magnitude larger than all the others. However, there is a sizable part in

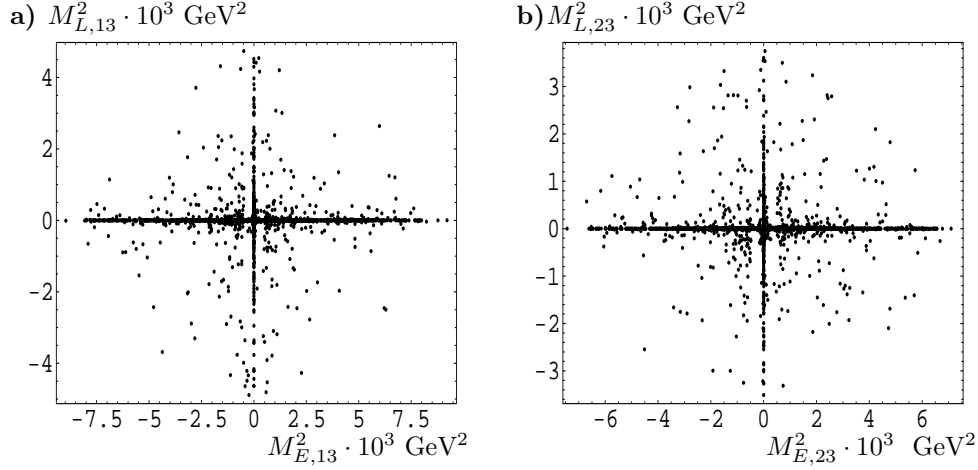


Fig. 1. Ranges for parameters inducing lepton number violation.

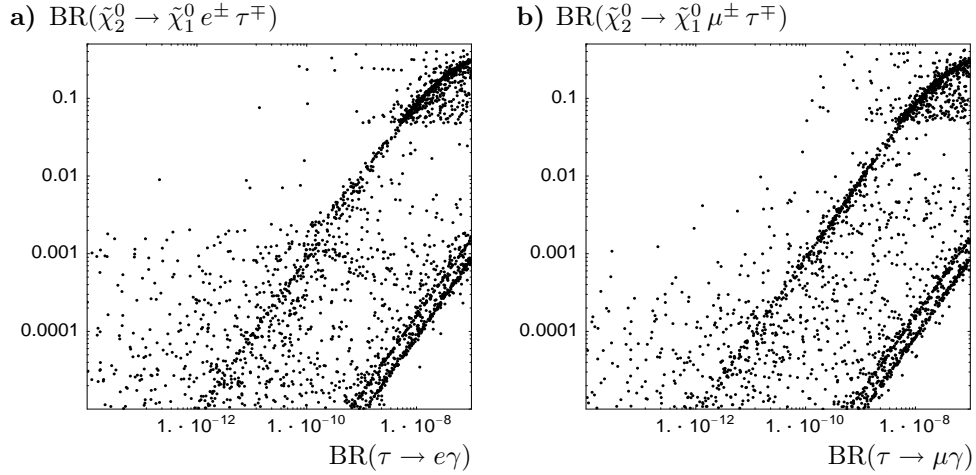


Fig. 2. Branching ratios for lepton number violating decays of the second lightest neutralinos as a function of branching ratios of rare lepton decays taking SPS1a as starting point and adding lepton flavour violating off diagonal entries.

parameters where at least two of the off-diagonal parameters have the same order of magnitude as shown in Fig. 1.

These parameters induce lepton number violating couplings to charginos and neutralinos which in turn lead lepton number violating decays such as $\tilde{\chi}_2^0 \rightarrow \tilde{e}_R \tau$, $\tilde{e}_R \rightarrow \mu \tilde{\chi}_1^0$ or $\tilde{e}_R \rightarrow \tau \tilde{\chi}_1^0$. In Fig. 2 we show examples of lepton flavour violating decays modes of the second lightest neutralino where we have summed over the intermediate slepton states. As can be seen these branching ratios can go up to 40%.

It has been shown in [10] that lepton number violating decay chains can be identified despite the considerable background processes stemming from decays of supersymmetric particles. This implies that lepton number violation in supersymmetric decays can be explored at the LHC. In addition these decay modes are important for the LHC when one considers the so-called edge variables discussed in [16]. These variables are extracted from decay chains such as $\tilde{q}_L \rightarrow q\tilde{\chi}_2^0 \rightarrow ql^\pm\tilde{l}_R^\mp \rightarrow ql^+l^-\tilde{\chi}_1^0$ and are very useful to measure not only mass differences of supersymmetric particles but also the mass of the lightest supersymmetric particle. The effect of the LFV modes is two-fold: On the one hand the reduce final states containing e^+e^- and $\mu^+\mu^-$ pairs which might deteriorate the accuracy of the mass measurements of selectrons and smuons. On the other hand the could increase the accuracy of the stau mass measurements as the final states do not only contain $\tau^+\tau^-$ pairs but also $e^\pm\tau^\mp$ and $\mu^\pm\tau^\mp$.

Finally we want to remark that in scenarios with large lepton number violation the discovery reach of LHC could be enlarged taking SPS1a as example. In this scenario the discovery of the lightest chargino is very difficult if not impossible at LHC [17] because the chargino decays with nearly 100% as follows: $\tilde{\chi}_1^+ \rightarrow \nu_\tau\tilde{\tau}_1^+ \rightarrow \nu_\tau\tau^+\tilde{\chi}_1^0$. In case of sizable lepton number violation in the right slepton sector the lighter stau can have large branching ratios into e or μ final states. We have found that in the above scanned parameter space the sum of the branching ratios $\text{BR}(\tilde{\tau}_1 \rightarrow e\chi_1^0) + \text{BR}(\tilde{\tau}_1 \rightarrow \mu\chi_1^0)$ can go up to 20% even in case where the branching ratios for rare τ decays are at a level of 10^{-10} . This could enhance considerably the discovery potential for the lightest chargino in this scenario.

3 Bilinear R-parity violation

In supersymmetric theories Majorana mass terms for left-handed neutrinos can be induced by introducing lepton-number and, thus, R-parity breaking terms in the superpotential. Adding bilinear terms to the MSSM superpotential is the simplest way to realize this idea in practice explaining successfully neutrino data (see e.g. [12] and references therein). In such a scenario an effective seesaw mechanism takes place where the neutralinos play the role of the right-handed neutrinos. This implies that various decay properties of the lightest supersymmetric particle (LSP) are correlated with neutrino properties, in particular with neutrino mixing angles [13, 14].

The Lagrangian of the model is obtained by adding bilinear terms breaking lepton number to the MSSM superpotential and consistently the corresponding terms to the soft SUSY breaking potential:

$$W_{\text{BRpV}} = W_{\text{MSSM}} - \varepsilon_{ab}\epsilon_i\hat{L}_i^a\hat{H}_u^b \quad , \quad V_{\text{soft}} = V_{\text{soft,MSSM}} - \varepsilon_{ab}B_i\epsilon_i\tilde{L}_i^aH_u^b \quad . \quad (5)$$

The latter induce vacuum expectation values v_i for the sneutrinos which are in turn responsible for mixing between standard model particles with supersymmetric particles. The mixing of neutrinos with neutralinos gives rise to one massive neutrino at tree level. The other two neutrinos obtain masses due to loop effects

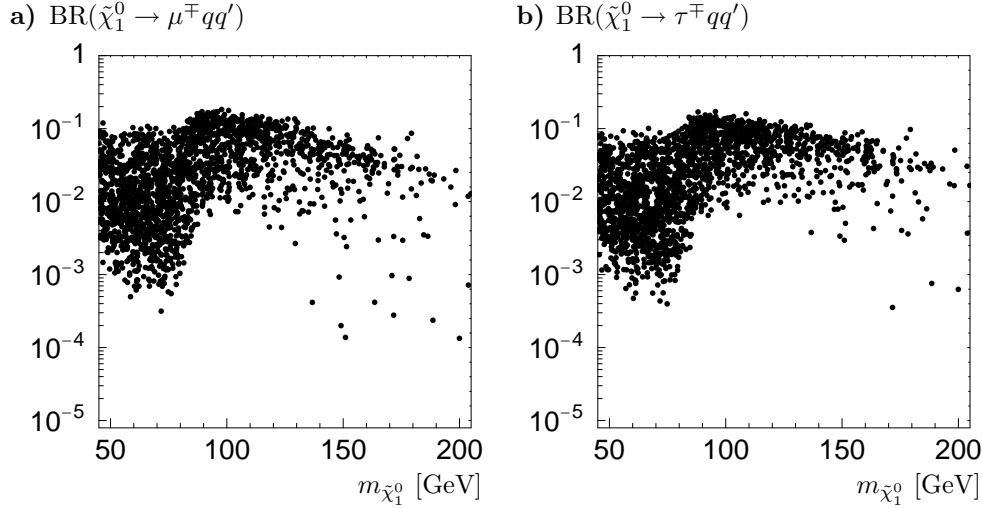


Fig. 3. Examples of branching ratios for semi-leptonic decays of the lightest neutralino as a function of $m_{\tilde{\chi}_1^0}$ scanning over the SUSY parameter space.

[12]. Assuming that the heaviest neutrino obtains its mass at tree level, the main features relevant for our current purpose are the following:

$$\tan \theta_{\text{atm}} = \left| \frac{\Lambda_2}{\Lambda_3} \right|, \quad \tan \theta_{\text{sol}} \simeq \left| \frac{\tilde{\epsilon}_1}{\tilde{\epsilon}_2} \right|, \quad U_{e3}^2 \simeq \frac{\Lambda_1^2}{\Lambda_2^2 + \Lambda_3^2} \quad (6)$$

$$\Lambda_i = \epsilon_i v_d + \mu v_i, \quad \tilde{\epsilon}_i = V_{ij}^{\nu, \text{tree}} \epsilon_j \quad (7)$$

where θ_{atm} is the atmospheric neutrino mixing angle, θ_{\odot} is the solar neutrino mixing angle and $V^{\nu, \text{tree}}$ is the tree level neutrino mixing matrix [12].

In this model the neutrino spectrum is hierarchical and hence the neutrino mass scales squared coincide with the the experimentally measured neutrino mass squared differences. This implies that the R-parity violating parameters are significantly smaller than the R-parity conserving ones: $|\epsilon_i| \ll |\mu|$ and $|v_i| \ll v_d$. This feature allows for the possibility that all R-parity violating couplings can be expanded in terms of the ratios [13, 12]

$$\frac{\epsilon_i}{\mu}, \quad \frac{\Lambda_i}{\sqrt{\text{Det}(\tilde{\chi}^0)}} \quad \text{or} \quad \frac{\Lambda_i}{\text{Det}(\tilde{\chi}^+)}. \quad (8)$$

This implies that the neutrino mixing angles in Eq. 6 can be expressed in ratios of couplings which themselves are related to ratios of branching ratios.

In the following we concentrate on the case that the lightest neutralino is the LSP. We have performed a scan over the MSSM parameter space and added the R-parity violating parameters such, that Δ_{atm}^2 and Δ_{sol}^2 and at least two of the three neutrino mixing angles are in the experimentally allowed range. In Fig. 3 the

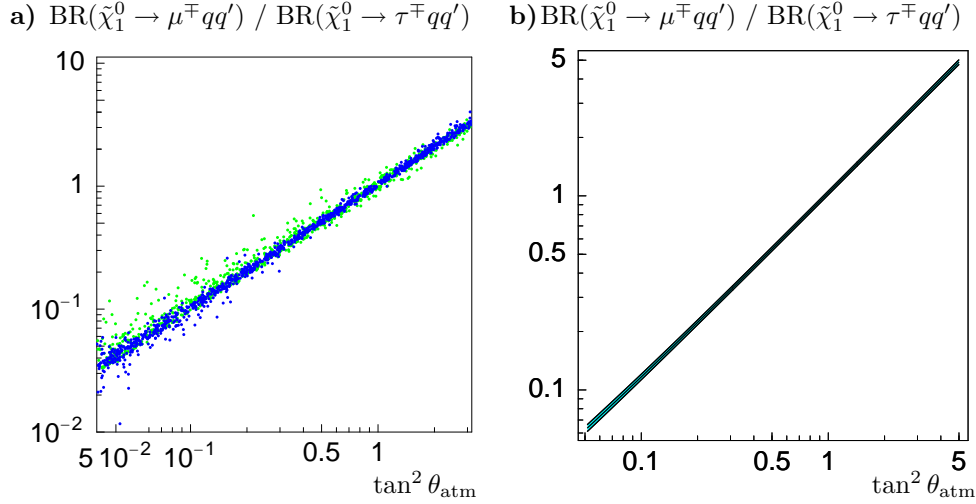


Fig. 4. Ratios of branching ratios of semi-leptonic neutralino decays as a function of the $\tan^2 \theta_{\text{atm}}$. In **a)** the predictions are shown without assuming any knowledge on the supersymmetric parameters whereas in **b)** it has assumed that the parameters are known with a precision of 10%.

branching ratios $\text{BR}(\tilde{\chi}_1^0 \rightarrow \mu^\mp qq')$ and $\text{BR}(\tilde{\chi}_1^0 \rightarrow \tau^\mp qq')$ are shown as a function of $m_{\tilde{\chi}_1^0}$. One sees that these branching ratios are in general in the range of a few per-mille up to about 20%. The importance of these decay modes is that they are correlated with the atmospheric neutrino mixing angle as shown in Fig. 4. In Fig. 4a we show the predictions of this model for the ratio $\text{BR}(\tilde{\chi}_1^0 \rightarrow \mu^\mp qq')/\text{BR}(\tilde{\chi}_1^0 \rightarrow \tau^\mp qq')$ scanning of the SUSY parameter space yielding a clear correlation with $\tan^2 \theta_{\text{atm}}$. The band collapses to a line if the SUSY parameters are known as shown in Fig. 4b. Here we have assumed that the SUSY parameters are known with a precision of 10% and we have taken into account the statistical error on these branching ratios assuming 10^5 identified neutralinos. In particular the masses and mixing angles of neutralinos, sbottoms and staus are important in this context [13].

In ref. [18] a Monte Carlo study has been performed where the ratio $\text{BR}(\tilde{\chi}_1^0 \rightarrow \mu^\mp qq')/\text{BR}(\tilde{\chi}_1^0 \rightarrow \tau^\mp qq')$ has been investigated within the SPS1a scenario adding R-parity violating parameters. Assuming an integrated luminosity of 100 fb^{-1} it has been shown that this ratio can indeed be measured with a precision of about three per-cent. This clearly shows that LHC is capable to test at least part of these correlations. The main ingredients for this statement are: (i) The considered semi-leptonic decay modes have a branching ratio of a few per-cent. (ii) The neutralino has a visible decay length. The latter is in particular useful to suppress background stemming from SM and SUSY processes.

4 Summary

We have discussed briefly the possibilities to study lepton number violating process at LHC in the context of supersymmetric theories. We have seen that LHC can explore lepton number violation in the decays of supersymmetric particles independent whether R-parity is conserved or violated. In the case of R-parity conservation we have commented on the effects of lepton flavour violating decay modes on edge variables and the discovery potential of LHC. In case of R-parity violation we have pointed out that it should be possible to measure at the LHC correlations between neutrino mixing angles and ratios of LSP branching ratios.

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